FERMILAB-Conf-02/268-E October 2002



# Searches at the Tevatron

W. Orejudos[a], for the CDF and D0 Collaborations

[a]Lawrence Berkeley National Laboratory,
1 Cyclotron Rd., Berkeley, CA, 94720 USA

Results of searches performed by CDF and D0 are presented. Most of the results are based on data taken during the 1994-95 data taking period (Run I), but some preliminary results from the current data taking period (Run II) are included.

## 1. Introduction

Run II of the Tevatron accelerator began in Spring 2001. The D0 and CDF experiments are currently recording collisions at a center-of-mass energy $\sqrt{s}$ of 1.96 GeV, an increase of ~10% with respect to the Run I center-of-mass energy. Both D0 and CDF have undergone substantial upgrades since the end of Run I and both have begun to present preliminary results based on Run II data. Both experiments have also continued to work on new analyses based on the Run I data.

## 2. Searches for new gauge bosons

CDF has previously looked for $W^{'}$ in the decay $W^{'} \to \ell\nu$ [1]. A new Run I analysis [2] looks for the decay $W^{'} \to$ tb, providing sensitivity in the case that the decay to leptons is suppressed. The analysis requires transverse energy $E_{\mathrm{T}} > 20$ GeV, an electron (muon) with $E_{\mathrm{T}} > 20$ GeV ($p_{\mathrm{T}} > 20$ GeV/$c$) and 2 or 3 jets ($j$) with $E_{\mathrm{T}} > 15$ GeV, where one of the jets has a high probability of coming from a b-quark. The $\ell\nu jj$ invariant mass, shown in Fig. 1, is formed by fixing the $\ell\nu$ mass to the mass of the $W$. No excess over the background expectation is seen in this distribution, and the $W^{'}$ mass $M_{W'}$ is excluded in the region 225 GeV/$c^2$ $< M_{W'} <$ 536 (566) GeV/$c^2$ for $M_{W'} >> M_{\nu_{\mathrm{R}}}$ ($M_{W'} < M_{\nu_{\mathrm{R}}}$). The D0 experiment has looked for $W^{'}$ using the dijet final state and has excluded the region 400 GeV/$c^2$ $< M_{W'} <$ 625 GeV/$c^2$ [3].

CDF has looked for $Z^{'}$ production in the Drell-Yan channel [4]. The Run I analysis requires two isolated, high $E_{\mathrm{T}}$ ($p_{\mathrm{T}}$) oppositely charged electrons (muons) and has set a lower limit on the $Z^{'}$ mass of 690 GeV/$c^2$. At Run IIa (the first ~2 fb$^{-1}$ of Run II data), $Z^{'}$ masses up to 1000 GeV/$c^2$ will be probed [5].

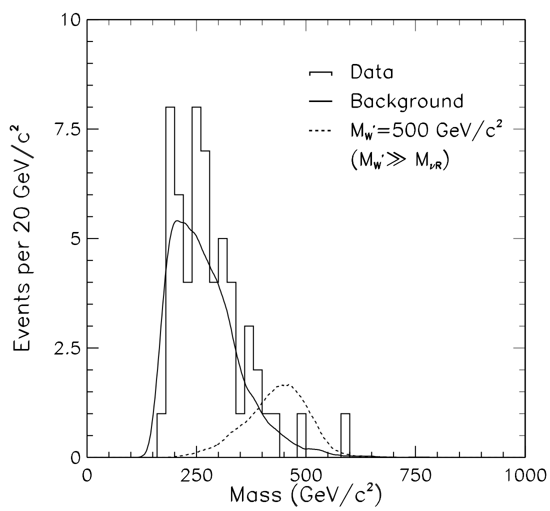


Figure 1. The $\ell\nu jj$ invariant mass distribution for the CDF $W^{'} \to$ tb analysis. The histogram shows the data, the solid line the background expectation and the dashed line the expectation for a $W^{'}$ with a mass of 500 GeV/$c^2$.

## 3. Searches for compositeness and technicolor

The Drell-Yan final state has also been used to search for other types of new physics. A limit on the mass of color singlet technirhos ($\rho_{\mathrm{T1}}$) and techniomegas ($\omega_{\mathrm{T1}}$) of 207 GeV/$c^2$ has been set by D0 at Run I using the $e^+e^-$ final state [6]. At Run IIa this search should be sensitive up to 410 GeV/$c^2$ [7]. D0 has also used this final state to set a lower limit on the quark-lepton compositeness scale of $\Lambda^- > 4.2$ ($\Lambda^+ > 3.3$) TeV assuming that the contact interaction and the Standard Model Lagrangian interact constructively (destructively) [8]. The corresponding reach at Run IIa is $\Lambda^- > 10$ ($\Lambda^+ > 6.5$) TeV [9].

D0 has searched for quark compositeness using the dijet final state. Limits of $\Lambda^- > 2.4$ ($\Lambda^+ > 2.7$) TeV have been set with the Run I data [10]. The same final state has been used by D0 to set a lower limit of 775 GeV/$c^2$ on the mass of excited quarks [3]. The Run IIa reach for this search is 940 GeV/$c^2$ [11].

Additional searches for technicolor have been performed in a variety of final states at Run I. CDF has searched for $\rho_{\mathrm{T1}}$ in the decay $\rho_{\mathrm{T1}} \to W\pi_{\mathrm{T1}} \to \ell\nu\mathrm{b}\bar{\mathrm{b}}$ [12]. The $\rho_{\mathrm{T1}}$ mass $M_{\rho_{\mathrm{T1}}}$ has been excluded in the region 170 GeV/$c^2$ $< M_{\rho_{\mathrm{T1}}} <$ 200 GeV/$c^2$, assuming that the $\pi_{\mathrm{T1}}$ mass $M_{\pi_{\mathrm{T1}}}$ is equal to about one-half of $M_{\rho_{\mathrm{T1}}}$. At Run IIa CDF will probe the region 160 GeV/$c^2$ $< M_{\rho_{\mathrm{T1}}} <$ 240 GeV/$c^2$ [7]. CDF has searched for $\omega_{\mathrm{T1}}$ in the decay $\omega_{\mathrm{T1}} \to \gamma\pi_{\mathrm{T1}} \to \gamma\mathrm{b}\bar{\mathrm{b}}$ [13]. The $\omega_{\mathrm{T1}}$ mass $M_{\omega_{\mathrm{T1}}}$ has been excluded in the region 240 GeV/$c^2$ $< M_{\omega_{\mathrm{T1}}} <$ 310 GeV/$c^2$ for $M_{\pi_{\mathrm{T1}}} =$ 120 GeV/$c^2$, and 140 GeV/$c^2$ $< M_{\omega_{\mathrm{T1}}} <$ 290 GeV/$c^2$ has been excluded for $M_{\pi_{\mathrm{T1}}} =$ 60 GeV/$c^2$. CDF has also searched for color octet technirhos ($\rho_{\mathrm{T8}}$) in the decay $\rho_{\mathrm{T8}} \to \pi_{\mathrm{LQ}}\pi_{\mathrm{LQ}} \to \mathrm{b}\nu\mathrm{b}\nu$ [14]. A limit on the $\rho_{\mathrm{T8}}$ mass $M_{\rho_{\mathrm{T8}}}$ of $M_{\rho_{\mathrm{T8}}} >$ 600 GeV/$c^2$ has been set. At Run IIa CDF will be sensitive to values of $M_{\rho_{\mathrm{T8}}}$ up to 850 GeV/$c^2$ [15].

CDF has searched for particles decaying to a $\mathrm{t}\bar{\mathrm{t}}$ final state [16]; this would be the favored decay mode of a leptophobic $Z^{'}$ found in certain models of topcolor [17]. The analysis of Run I data looked for $\mathrm{t}\bar{\mathrm{t}}$ events with one decay $\mathrm{t} \to \mathrm{b}\ell\nu$ and another decay $\mathrm{t} \to \mathrm{bq}\mathrm{q}^{'}$. A fit was performed for each event to get the mass of the $\mathrm{t}\bar{\mathrm{t}}$ system, $M_{\mathrm{t}\bar{\mathrm{t}}}$. The distribution of $M_{\mathrm{t}\bar{\mathrm{t}}}$ was found to be consistent with the background expectation, and a lower limit on the leptophobic $Z^{'}$ mass $M_{\mathrm{Z}'}$ of 780 (480) GeV/$c^2$ was set for a natural width $\Gamma_{\mathrm{Z}'}$ of $0.04M_{\mathrm{Z}'}$ ($0.012M_{\mathrm{Z}'}$). At Run IIa CDF will be sensitive to leptophobic $Z^{'}$ masses up to 1100 GeV/$c^2$ for $\Gamma_{\mathrm{Z}'} = 0.04M_{\mathrm{Z}'}$ [15].

## 4. Search for heavy, long-lived charged particles

A search for CHAMPS, heavy charged particles long-lived enough to leave the detector, has been performed by CDF at Run I [18]. The analysis looks for high $p_{\mathrm{T}}$ charged particles with a large ionization energy loss. No evidence of a signal was found and a lower limit of 220 (190) GeV/$c^2$ has been set on the CHAMP mass in the context of a long-lived up (down)-type 4$^{\mathrm{th}}$ generation quark. CDF is also developing an analysis [19] for Run II which will use the new time-of-flight (TOF) detector installed during the upgrade. The analysis requires a high $p_{\mathrm{T}}$ charged particle with a large time-of-flight. A total of $2.2 \pm 0.8$ events from background sources are expected in the $16.5 \pm 1.7$ pb$^{-1}$ of Run II data that have been analyzed thus far.

## 5. Final states with photons

CDF has searched for new physics in the Run I diphoton sample [20]. Two isolated photons, each with $E_{\mathrm{T}} > 22$ GeV, are required in the analysis. The main background comes from jets which fake photons. No evidence for new physics was found in this sample. A subset of this sample was used to search for a Higgs which is produced in association with a $W$ or $Z$ and which decays to two photons [20]. Events with a $W$ or $Z$ are selected by asking for an electron (muon) with $E_{\mathrm{T}} > 20$ GeV ($p_{\mathrm{T}} > 20$ GeV/$c$), or for missing $E_{\mathrm{T}} > 20$ GeV, or for two jets with $E_{\mathrm{T}} > 15$ GeV that form an invariant mass between 40 and 130 GeV/$c^2$. No excess above the Standard Model expectation is found in the resulting sample and a lower limit on the mass of a bosophilic Higgs of 82 GeV/$c^2$

is set.

CDF has also performed a model independent search for new physics with photons in the final state [21]. Several final states were defined, based on the presence of leptons, photons, and missing $E_{\mathrm{T}}$. One such final state is defined by the presence of a photon with $E_{\mathrm{T}} > 25$ GeV, an electron (muon) with $E_{\mathrm{T}} > 25$ GeV ($p_{\mathrm{T}} > 25$ GeV/$c$), missing $E_{\mathrm{T}} > 25$ GeV, and an azimuthal angle between the photon and lepton which is less than 150°. Most of the events which produce this final state are expected to come from $(W/Z)\gamma$ production or from events with a real lepton and a jet which fakes a photon. A total of $7.6 \pm 0.7$ events are expected in the Run I data while 16 events are observed.

## 6. Search for large extra dimensions

In theories of large extra dimensions [22], gravitons may be detected at energies currently accessible by the Tevatron experiments. Searches by D0 and CDF can be divided into two categories: searches in the diphoton or dilepton final state for evidence of graviton exchange and searches in final states with large missing $E_{\mathrm{T}}$ for direct graviton production.

In graviton exchange diagrams a virtual graviton is produced which couples to a $\gamma\gamma$ or $\ell^+\ell^-$ final state. D0 has combined their Run I diphoton and dielectron samples and performed a search [23] by requiring two electromagnetic objects with $E_{\mathrm{T}} > 45$ GeV. In addition, the missing $E_{\mathrm{T}}$ is required to be less than 25 GeV. The main backgrounds in this search come from Drell-Yan and $\gamma\gamma$ processes, as well as events in which two jets fake a photon or electron. The analysis looks at the angular distributions of the electromagnetic objects as well as their invariant mass. No deviation from the Standard Model expectation is observed, and a lower limit on the effective Planck scale of $M_{\mathrm{S}} > 1.1$ (1.0) TeV is set in the Hewett convention [24], assuming constructive (destructive) interference between the Kaluza-Klein and Standard Model contributions.

In direct graviton production the graviton escapes the detector, producing missing $E_{\mathrm{T}}$. A gluon or a photon can also be produced in the event. D0 has performed a search at Run I for the graviton-gluon final state [25]. The analysis looks for events that have a single jet with $E_{\mathrm{T}} > 150$ GeV, missing $E_{\mathrm{T}} > 150$ GeV, and no other jets with $E_{\mathrm{T}} > 50$ GeV. The main backgrounds come from the processes $Z \to \nu\bar{\nu}$ + jets, $W \to \tau\nu$ + jets, and from QCD and cosmics rays. A total of $38.0 \pm 9.6$ events are expected from background processes, while 38 are actually observed. The lack of observation of a signal leads to a limit of $M_{\mathrm{S}} > 886$ (617) GeV for 2 (7) large extra dimensions.

CDF has searched for direct graviton production at Run I in the graviton-photon final state [26]. The analysis looks for events that have a photon with $E_{\mathrm{T}} > 55$ GeV, missing $E_{\mathrm{T}} > 45$ GeV, and no jets with $E_{\mathrm{T}} > 15$ GeV in the event. The main backgrounds come from $Z \to \nu\bar{\nu}\gamma$ and from cosmic rays. A total of $11.0 \pm 2.2$ events are expected from the background sources, and 11 events are actually observed. Again, no signal is observed and a limit of $M_{\mathrm{S}} > 549$ (602) GeV is set for 4 (8) large extra dimensions.

D0 has also performed a search for graviton exchange using $9.85 \pm 0.38$ pb$^{-1}$ of data from Run II [27]. Two electromagnetic objects with $E_{\mathrm{T}} > 25$ GeV are required in the analysis. The missing $E_{\mathrm{T}}$ is required to be less than 30 GeV. No evidence of a signal is seen, and a limit of $M_{\mathrm{S}} > 0.82$ TeV is set in the Hewett convention, assuming constructive interference between the Kaluza-Klein and Standard Model contributions. More data needs to be analyzed in order to improve on the Run I result.

## 7. Leptoquark search at Run II

D0 has looked for first generation leptoquark pair production in the Run II data [27]. Each leptoquark would decay to an electron and a quark; D0 looks for this final state by requiring two electromagnetic clusters with $E_{\mathrm{T}} > 25$ GeV and at least two jets with $E_{\mathrm{T}} > 20$ GeV. The jets are required to not form an invariant mass near that of the $Z$. The main backgrounds to this search come from Drell-Yan production and from jets faking electrons. Fig. 2 shows the scalar sum of

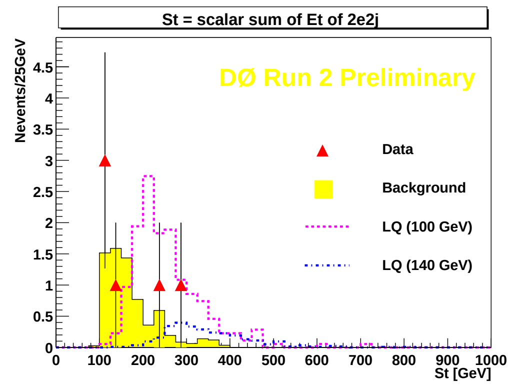


Figure 2. Scalar sum of the two electromagnetic clusters and the two highest $E_\mathrm{T}$ jets. The solid histogram is the Standard Model expectation , the points are data and the dashed (dashed-dotted) lines show the expectation for a leptoquark mass of 100 (140) GeV/$c^2$.

the two electromagnetic clusters and the 2 highest $E_\mathrm{T}$ jets. No evidence of a signal was seen in the $8.0 \pm 0.8$ pb$^{-1}$ of Run II data that was analyzed, leading to a lower limit on the leptoquark mass of 113 GeV/$c^2$. More data needs to be analyzed in order to improve on the Run I result [28].

## 8. Conclusion

In recent years the D0 and CDF experiments have continued to perform searches for new physics using the Run I data. Run II is now underway and preliminary search results are starting to appear. The next few years promise to be a very exciting time for D0 and CDF as both experiments continue to search the Run II data for hints of new physics.

## REFERENCES


1. T. Affolder *et al.*, CDF Collaboration, Phys. Rev. Lett. **87**, 231803 (2001).
2. D. Acosta *et al.*, CDF Collaboration, hep-ex/0209030 (2002).
3. C. Hebert for the D0 Collaboration, Presentation given at the APS 2002 Spring Meeting, Albuquerque, NM, April 20-24 2002.
4. F. Abe *et al.*, CDF Collaboration, Phys. Rev. Lett. **79**, 2191 (1997).
5. R. Blair *et al.*, CDF Collaboration, FERMILAB-PUB-96/390-E (1996).
6. V.M. Abazov *et al.*, D0 Collaboration, Phys. Rev. Lett. **87**, 061801 (2001).
7. K. Lane, hep-ph/0006143 (2000).
8. B. Abbott *et al.*, D0 Collaboration, Phys. Rev. Lett. **82**, 4769 (1999).
9. K. Cheung and R. Harris, hep-ph/9610382 (1996).
10. B. Abbott *et al.*, D0 Collaboration, Phys. Rev. Lett. **82**, 2457 (1999).
11. R. Harris, hep-ph/9609319 (1996).
12. T. Affolder *et al.*, CDF Collaboration, Phys. Rev. Lett. **84**, 1110 (2000).
13. T. Affolder *et al.*, CDF Collaboration, Phys. Rev. Lett. **83**, 3124 (1999).
14. T. Affolder *et al.*, CDF Collaboration, Phys. Rev. Lett. **85**, 2056 (2000).
15. T.L. Barlow *et al.*, hep-ph/0201243 (2002).
16. T. Affolder *et al.*, CDF Collaboration, Phys. Rev. Lett. **85**, 2062 (2000).
17. T. Affolder *et al.*, CDF Collaboration, FERMILAB-FN-687 (1999).
18. A. Connolly for the CDF Collaboration, FERMILAB-CONF-99/092-E (1999).
19. CDF Collaboration, internal note 5997 (2002).
20. T. Affolder *et al.*, CDF Collaboration, Phys. Rev. D **64**, 092002 (2001).
21. D. Acosta *et al.*, CDF Collaboration, Phys. Rev. D **66**, 012004 (2002).
22. N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. B **429**, 263 (1998).
23. B. Abbott *et al.*, D0 Collaboration, Phys. Rev. Lett. **86**, 1165 (2001).
24. J.L. Hewett, Phys. Rev. Lett **82**, 4765 (1999).
25. S. Hagopian for the D0 Collaboration, hep-ex/0205048 (2002).
26. D. Acosta *et al.*, CDF Collaboration, FERMILAB-PUB-02/119-E.
27. D0 Collaboration, internal note 3995 (2002).
28. B. Abbott *et al.*, D0 Collaboration, Phys. Rev. Lett. **79**, 4321 (1997).